AFML–TR–73–288

FRACTURE TOUGHNESS AND FATIGUE PROPERTIES OF TITANIUM LAMINATE COMPOSITES PRODUCED BY CONTROLLED DIFFUSION BONDING

D. O. COX
A. S. TETELMAN

FAILURE ANALYSIS ASSOCIATES

TECHNICAL REPORT AFML–TR–73–288

OCTOBER 1973

AIR FORCE MATERIALS LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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FOREWORD

This report was prepared by Failure Analysis Associates, Stanford, California. The work was performed under USAF Contract No. F33615-72-C-2096. The contract was initiated under Project No. 738106, "Engineering and Design Data", and directed by Mr. C. L. Harmsworth, Systems Support Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

The authors wish to acknowledge Dr. Howard Hamilton of the Los Angeles Division of Rockwell International Corp., who supervised fabrication of the billets for his excellent assistance, UCLA for providing the facilities for testing the material, and Dr. D. Broek of NLR for his stimulating conversation.

This report covers work conducted from June 1972 to August 1973.

The report was submitted by the authors in October 1973.

This technical report has been reviewed and is approved.

A. OLEVITCH
Chief, Materials Engineering Branch
Materials Support Division
Air Force Materials Laboratory

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ABSTRACT

An investigation of the use of laminate composites containing a weak interface to increase the fracture toughness of high strength titanium alloy has been conducted. Two billets were fabricated from 0.010" Ti-6Aℓ-4V material using a diffusion bonding process. Thin metal foils were used as interleaf materials. Results indicate that the use of a 0.0015" Aℓ foil as an interleaf leads to delamination ahead of the crack tip in the arrester orientation, and effectively blunts the crack.

In the divider orientation, splitting of the Aℓ interleaf and plane stress fracture did not lead to the increase in toughness expected over thicker material. However, tests indicate that the base metal used in fabrication has a low K_c value, which may account for this effect.

It was found that a 0.001" commercially pure titanium foil used as an interleaf will not lead to delamination and splitting. Diffusion during the bonding process causes formation of a uniform material with no weak interface. Therefore, no delamination or splitting could occur in the composite material.

It was also found that a propagating fatigue crack can be arrested at the interleaf in the arrester orientation. It was also determined that the crack growth rates of material which splits in the divider orientation are similar to rates obtained from full strength material.

Introduction

In an effort to obtain a high yield strength and high toughness
material, a laminate structure composed of high strength titanium
sheet with a weaker interface material has been studied previously.[1]
In the past investigation, billets which incorporated 0.040 in. 6Aℓ-4V
titanium with various thin (< .010 in.) interleaf materials were fabricated
by diffusion bonding at Rockwell International, Los Angeles Division.
Toughness tests were made using precracked Charpy specimens machined from
the fabricated billets.

It was found that delamination ahead of the crack tip in the arrester
orientation (Fig. 1) led to crack blunting, and gross yielding of the
material occurred before failure by mechanical instability. In the divider
orientation (Fig. 1), where splitting of the interface causes the laminate
material to behave as the sum of many thin sheets loaded in plane stress,
no significant increase in toughness was found. This is not the expected
result for material of this orientation, since the plane stress toughness
can be a factor of two or three times greater than the plane strain
value.[2] It was concluded that this result occurred because the sheet
thickness chosen for the base metal (0.040 in.) was below the thickness at
which maximum toughness is observed (see Fig. 2).

Our previous work also showed that a thin interleaf material with a
relatively low yield strength leads to delamination and splitting. Material
fabricated with a commercially pure aliminum interleaf 0.0015" thick de-
laminated and split while a 0.005" commercially pure titanium interleaf did
not. It was concluded that a thinner CP titanium foil might lead to

delamination and splitting and high toughness, at least in the arrester orientation. A titanium interleaf for titanium base metal is attractive, since it would eliminate the possibility of corrosion, which might occur with an aluminum interleaf.

Purpose of Present Study

This program was conducted to further determine the potential for using the diffusion bonded laminates to improve toughness and fail-safe characteristics of high strength titanium alloys. The previous study indicates that delamination and splitting of the interface in diffusion bonded laminates is possible and this leads to high toughness in the arrester geometry. The present work was designed to investigate three phenomena:

1) whether it would be possible to obtain an increase in toughness in the divider orientation, by choosing the thickness of the base metal material at which its fracture toughness is a maximum (Fig. 2);

2) whether a very thin commercially pure titanium foil (thinner than tried previously) can be used to obtain delamination and splitting in the arrester and divider orientations;

3) whether the fatigue crack propagation rates in these laminate materials compared favorably with rates measured on wrought material.

Materials and Fabrication

The material selected for the study was 6Aℓ-4V titanium mill annealed sheet (AMS 4911) 0.100" in thickness. This thickness was chosen since it is near the optimum thickness which leads to maximum toughness as shown in Fig. 2. Material from two different heats were used. During fabrication of the billets the sheets from the two heats were alternated. The physical properties and chemical analysis for the two heats are shown in Tables I and II, respectively.

The two billets fabricated incorporated metal foils as an interleaf material. The first billet fabricated (hereafter referred to as Billet A) had a commercially pure aluminum foil 0.0015" in thickness (1100 alloy). This was a typical heavy duty household foil, and no mechancial testing or chemical analyses was made on the materials. The second billet (here-after referred to as Billet B) had a 65A grade commercially pure titanium foil 0.001 " thick, which was obtained in the annealed condition (AMS 4900B). The physical properties and chemical analysis of this foil are also shown in Tables I and II.

In addition to the above billets, material from the fully bonded (i.e., no interleaf incorporated) billet fabricated for the previous work was also used in this study. This billet [Billet #1 in Ref. (1) and designated as such hereafter in this report] was fabricated from 0.040" 6Aℓ-4V titanium sheet (ASM 4911). For physical properties and chemical analysis of the four heats used in fabrication of this billet [see Ref. (1)].

All three billets were fabricated with a full strength bond between the laminae. Billet #1 was seven inches wide by seven inches long by 2.4' inches thick. Billets A and B were 15 inches square by 0.6 inches thick. The

actual bonding was done under sub-contract to the Los Angeles Division of Rockwell International, under the supervision of Dr. Howard Hamilton. The titanium sheet, retort, and tooling were prepared using established cleaning procedures.[1] All diffusion bonding was conducted under vacuum of less than 10^{-4} torr. A heavy retaining ring, or yoke, was used to assure side restraint and to prevent excess lateral deformation. Time, temperature, and pressure depended on interleaf material used. The parameters used for each of the billets are shown in Table III. Typical microstructure of the as-fabricated billets are shown in Fig. 3.

Testing Procedures

Because of the very limited nature of the program, it was desirable to use relatively small, inexpensive specimens for the determination of fracture toughness and fatigue properties of the laminate materials. Therefore, precracked Charpy specimens (Fig. 4) were initially used in the study. Subsequently, it was believed that in the divider orientation the depth of the Charpy specimen might be insufficient to develop full shear lips,and larger three-point bend specimens, (shown in Fig. 5) were also machined. Although the specimens do not meet ASTM specimen criteria, and the results are not "valid" K_{Ic} values, the values we obtained are useful for comparing the relative toughness characteristics of the materials evaluated.

All tests were conducted on material in the as-fabricated condition. Since all the alloys used in fabrication of the billets were in the mill annealed state at the time of fabrication, the laminated material as tested would also be in a mill annealed condition.

Both the precracked Charpy and the larger three-point bend specimens were used in the fracture toughness study. Precracking of the Charpy specimens was done using a Krouse fatigue machine while the larger specimens were precracked using an MTS closed loop system. In both cases, apprximately 50,000 cycles were used to obtain a fatigue crack of about 0.040 to 0.060" in depth. The fracture testing of the Charpy specimens was done on an Instron tensile testing machine. The tests were run at room temperature with a cross-head speed of 0.1 in/min. The larger specimens were tested on the MTS machine using a ram speed of 0.15in/min.

The fracture toughness values were obtained in the following manner. For the three-point bend specimen, it has been shown that the crack tip

stress intensity factor, K, is given by

$$K = Y \frac{6M}{BM^2} \sqrt{a} \qquad (1)$$

The applied moment, M, is given by

$$M = \frac{PL}{4} \qquad (2)$$

where P is the applied load and L is the loading span. Thus

$$K = Y \frac{6PL}{4BW^2} \sqrt{a} \qquad (3)$$

where W is the depth, B is the specimen thickness, a is the total crack depth, and Y is the K calibration. A curve showing the K calibration for three-point bend specimens as a function of a/W has been calculated by Gross and Srawley.[4] Using the curve, the specimen dimensions, and the maximum applied load as determined from the load deflection curve, the fracture toughness was obtained.

All fatigue tests were done using the MTS closed loop system. Testing was done in air at room temperature using a cyclic rate of 30 cycles/sec. The stress ratio for all tests was R≈0, although a small minimum load was necessary to keep the specimen and jig fixed in the machine. Two methods of analysis were used. A few specimens were cycled at a given initial maximum load and the total number of cycles to failure was determined. The remaining specimens were used to determine crack propagation rates as a function of stress intensity ·(da/dN vs. ΔK). A specimen was cycled a given number of times and the load was monitored using an oscilloscope. The specimen was then removed from the testing machine and the length of the crack was measured on both sides of the specimen. The crack length was

taken as the average of the two measured values. Knowing the number of cycles to which the specimen was subjected, and from measurements of crack length before and after a given period of cyclic loading, the crack growth per cycle could be determined. The ΔK was found from the average crack length (original crack length plus half the change in crack length), and the average maximum and minimum loads over the cyclic increment. The specimen was then placed back into the MTS machine and the process repeated. Crack growth of approximately 0.05 to 0.10 inches was obtained between measurements. In this manner one specimen could be used to obtain more than one data point. Using this method a comparison between da/dN rates for the three types of materials was made.

In addition material from Billets A and B has been sent to AFML. Thumbnail crack specimens machined from the supplied material will be tested by AFML to determine fatigue properties in the arrester orientation.

Results

A. Fracture Toughness Tests

Individual sheets of the 0.10 inch 6Aℓ-4V titanium material used
in billet fabrication were tested to determine the value of K_c.
Charpy size specimens were notched, precracked and tested in three-point
bending. Results of three tests indicate the K_c of the material used
in fabricating the billets was 60 Ksi$\sqrt{in.}$ which is considerably below
the value ($\sim$ 140 Ksi $\sqrt{in.}$) reported in Ref. (2) [Fig. 2]. No K_c values
were obtained from the larger specimens. The low value obtained from
the small specimens may indicate that, in this material, K_c is a function
of ligament depth (W-a) as well as sheet thickness, and that K_c increases
with (W-a). K_Q tests on Billet #1 done previously (1) are shown in
Table IV as well as the results of the larger three-point bend specimens.

Billet A containing the 0.0015 inch aluminum interleaf showed excellent
delamination and splitting properties. Toughness values for this material
are shown in Table IV. In the arrester orientation, delamination occurred
ahead of the crack tip, which led to crack blunting and crack arrest. No
toughness value could be measured. Fig. 6 shows a typical specimen with
the arrester orientation after testing.

In the divider orientation splitting occurred (Fig. 7) but the toughness
value measured (62 Ksi $\sqrt{in}$) is less than the plane strain value. (76 Ksi $\sqrt{in.}$).
It was believed that a possible reason for this effect was the limited
legament depth of the Charpy specimen, which did not allow development
of full shear lip fracture before instability. Consequently, the larger
specimens were machined and tested. As shown in Table IV, the toughness
of the larger specimens were 20% higher than that of the smaller specimens.

However, no large (100%) increase in toughness was achieved, as expected from Fig. 2. This would indicate that still wider specimens might be required to determine the full potential of delamination as a means of increasing toughness in the divider orientation.

Billet B containing 0.001 inch CP titanium interleaf did not delaminate in the arrester orientation, nor did splitting occur in the divider orientation. This was noted for both the Charpy samples and the larger three-point bend specimens. Toughness values for this billet are shown in Table IV and the fracture appearance is shown in Fig. 7.

B. Fatigue Tests

Our results indicate that a propagating fatigue crack can be effectively stopped in the arrester geometry if delamination occurs at the crack tip. This effect can be observed in Fig. 8, where a specimen of Billet A, tested in the arrester orientation, has been cycled in fatigue at a K-level of 11.4 Ksi $\sqrt{\text{in}}$. However, specimens of the same orientation from Billet B did not arrest the propagating fatigue crack. This is consistent with our observation that crack arrest does not occur in the fracture toughness tests. Further information on the crack arrest capabilities of Billets A and B will be obtained when testing of thumbnail crack specimens is completed at AFML.

A majority of the work done on fatigue properties in these materials was conducted in the divider orientation. Total cycles to failure were determined on one large three-point bend specimen from each of the three billets. The specimens were precracked and then cycled at constant peak load of 1400 lbs. with the stress ratio approximately equal to until total failure occurred. Table V shows the results, which indicate that

the fatigue properties are not significantly affected when splitting takes place. The total cycles to failure for Billet A are essentially equivalent to those measured in the other two billets in which splitting did not occur.

The remaining specimens were used to determine crack growth rates in the divider orientation as a function of ΔK. The results of these tests are shown in Table VI and are plotted in Fig. 9. They also indicate that there is little difference in propagation-rates between the material which split and the material which does not split, but there is considerably more scatter when splitting occurs.

There is a large amount of scatter in the experimental results of Billet A when splitting occurred. Fig. 10 shows the data from Billet A by specimen. Specimens from this billet showed a large difference in crack length when measured on one face, as compared to the opposite face, during testing. A crack would initiate and be visible on one side of the specimen, although no evidence of cracking would appear on the opposite side. The initial crack would propagate for a significant distance (more than 0.10 inches in some cases) before a crack appeared on the other side of the specimen.

The fatigue fracture appearance of specimens from the three billets are shown in Fig. 10. There is a small amount of crack channeling visible in the specimens of Billet A (see also Fig. 11). However, in no case did the fatigue crack propagate over an entire single layer before cracking initiated in an adjoining laminate.

DISCUSSION

Delamination and splitting took place in specimens from Billet A while these effects did not occur in Billet B. In previous tests, the 0.005" CP foil was visible after diffusion bonding. Examination of the microstructure of Billet B (Fig. 3c) indicates that the 0.001 CP titanium foil used as the interleaf material here was not of sufficient thickness. There is little evidence that a separate foil had been bonded to the base metal. During fabrication interdiffusion of the titanium foil and base alloy caused the formation of a continuous material and the removal of the weak interface. Without a low strength interface, delamination and splitting cannot take place. If a slightly thicker foil had been used, it is possible that the soft interface would have been retained and better fracture characteristics would be realized.

When splitting did occur in the divider orientation, the expected increase in toughness has not been realized, either in Billet A here, or in the work done previously. The data shown in Fig. 2 indicates that there should be a large increase in toughness when the fracture mode is plane stress (shear) rather than plane strain (flat). However, recent work done at Naval Research Laboratory concerning the effect of sheet thickness on K_c of high strength alloys indicates that a large difference in toughness between thin sheet and bulk material[5,6] is not always realized.

Fig. 12 shows data obtained at NRL on 6Aℓ-4V titanium material with a yield strength of 150 Ksi. The data indicate that there is not a large increase in toughness in sheet material, at least over thicknesses up to 0.125 inches, compared with typical plane strain K_{Ic} values (80 Ksi$\sqrt{in}$).

The NRL material is of a higher strength level than the annealed material used in the present study. However, the results of tests on the 0.10" material used in fabrication of Billets A and B indicate that the same effect may exist for annealed material as well. The value of 60 Ksi$\sqrt{\text{in}}$. obtained from our testing is much less than would be expected from the data of Fig. 2, but is consistent with the NRL results.

The low toughness values obtained for the divider orientation of Billet A (62 Ksi$\sqrt{\text{in}}$.) are reasonable if the toughness of the sheet material used in fabrication is this low (60 Ksi$\sqrt{\text{in}}$.) As shown in Fig. 7, complete shear lips develop early in the fracture (even in the smaller Charpy specimen), and there is only a small region of flat, plane strain fracture adjacent to the precrack. The low toughness of the 6Aℓ-4V titanium sheet material used in fabrication leads to the low toughness of the laminate composite, even though splitting results in plane stress failure.

Our results have shown that the crack stopping capabilities of the arrester orientation also apply to fatigue crack propagation. The crack travels to the interface and is effectively blunted. Initial results of tests on thumbnail crack specimens tested at AFML indicate that further crack growth will occur along the interleaf rather than through the base metal. An example of this effect is shown in Fig. 13. This effect will lead to large improvements in fatigue life and to easier detection of propagating cracks prior to instability.

In the divider orientation, a material which splits during fast fracture appears to have the same fatigue properties as the other materials which do not split. However, it is conceivable that in large test specimens

or in actual structures an improvement may be found because the mode of propagation of the fatigue crack can change from tension to shear.

A fatigue crack starts to propagate as a plane strain, mode I crack As the crack grows in length, the size of the plastic zone ahead of the crack increases. When the plastic zone size approaches the thickness of the sheet material, plane stress can develop and a transition to shear mode fatigue crack propagation can occur. This effect is shown schematically in Fig.

The fracture surface of all divider specimens tested in fatigue is flat and exhibits no shear type propagation. The lack of any transition in the present work may be explained by the small size of the specimens (small crack lengths) and relatively small stress intensities used in the testing $(\frac{K_{max}}{B} < 1.8)$.

From the above discussion it appears that as the thickness of the base metal sheet used in the laminate decreases, the transition to plane stress fracture will occur sooner, and the crack propagation rates will be lower. This effect is shown for a high strength aluminum alloy in Fig. 15. In thicker sheet material, a larger plastic zone size and longer crack are required before the transition will occur to plane stress propagation.

This raises the question of priorities in design of laminate composites of this type. Should the sheet thickness be chosen to optimize fast fracture properties (K_c) or fatigue properties? Since the optimum sheet thickness for fatigue propagation resistance may be below the thickness required for maximum toughness, some trade-offs will be required. However, as discussed previously, there may not be a thickness where K_c is significantly higher than K_{Ic} (in the divider orientation); in this instance, fatigue properties should be optimized by decreasing laminate thickness.

CONCLUSIONS AND RECOMMENDATIONS

The effectiveness of a diffusion bonded laminate composite in improving fracture and fatigue characteristics of high strength titanium has been shown. In the arrester orientation delamination ahead of the crack tip leads to crack blunting both in fast fracture and fatigue. This delamination may be achieved with thin aluminum foils, diffusion bonded to the mill annealed titanium base laminates.

In the divider orientation, splitting of the interface causes the material to behave as the sum of many thin sheets. However, for high strength alloys such as the 6Aℓ-4V titanium used in this work, splitting may not lead to significant increases in toughness, since the K_c for the sheet material may not differ much from the plane strain toughness, K_{Ic}.

In terms of resistance to fatigue crack propagation, the divider orientation has the same fatigue properties whether or not delamination occurs during fast fracture. It is believed that if fatigue occurs at higher stress intensity levels, or in a composite containing thinner base metal, a transition to plane stress propagation will occur which would lead to a decrease in da/dN at a given ΔK. Further work using larger specimens and billets fabricated with thinner base metal material should be studied to see if this expected improvement can be realized.

It has been found that a 0.001" commercially pure titanium foil is too thin to produce a weak interface, while the previous work[1] showed that a 0.005" CP titanium foil was too thick to give delamination and splitting. Problems with corrosion might probably develop if the aluminum foil is used as an interleaf, or when the material is joined using a braze

alloy. Corrosion would not be a problem if a CP titanium foil could be used. Therefore, further work using other CP foil thicknesses and strength levels should be conducted to determine the feasibility of using titanium foil as an interleaf material. Similarly, corrosion and corrosion fatigue tests should be conducted on the laminates bonded with aluminum foil.

The use of multi-laminate diffusion bonded composites containing weak interfaces has a great potential for practical applications. Further work must be done to study and improve the properties of such materials. Work to optimize the interleaf material should be conducted, especially the use of commercially pure titanium when used in conjunction with 6Aℓ-4V titanium. More work on fatigue properties in both the arrester and divider orientation, particularly a study of the fatigue near stress concentrations, and a study of the corrosion characteristics must be conducted before these materials can be incorporated in actual components.

REFERENCES

1. Cox, D.O. and A.S. Tetelman,"Improved Fracture Toughness of Ti-6Al-4V through Controlled Diffusion Bonding," Technical Report AFML-TR-71-264, 1972.

2. Wilhem, D.P., "Fracture Mechanics Guidelines for Aircraft Structural Applications," Technical Report AFFDL-TR-69-111, 1970.

3. Hahn, G.T. and A.R. Rosenfield, Applications Related Phenomena in Titanium Alloys, ASTM STP 432, p. 5.

4. Brown, W.F. and J.E. Srawley, Plain Strain Crack Toughness Testing of High Strength Metallic Materials, ASTM STP 410, 1966, p. 13.

5. Freed, C.N., A.M. Sullivan, and J. Stoop, "Effect of Sheet Thickness on the Fracture-Resistance K_c Parameter for Titanium Alloys," NRL Report No. 7464, 1972.

6. Sullivan, A.M. and J. Stoop, "Effect of Sheet Thickness on the Fracture-Resistance Parameter K_c for Steel," NRL Report No. 7601, 1973.

7. Broek, D., "Failsafe Design Proceedures," National Aerospace Laboratory, The Netherlands, NLR MP 72021 U, 1972.

APPENDICES

APPENDIX I

TABLES

Table I--Physical properties of 0.100 inch Ti-6Aℓ-4V and 0.001 inch CP titanium foil used in the study.

MATERIAL (HEAT)	YIELD STRENGTH (ksi)	TENSILE STRENGTH (ksi)	ELONGATION IN 2" (%)
Ti-6Aℓ-4V (1)	133	143	15
Ti-6Aℓ-4V (2)	129.3	136	15
CP Ti	62.9	72.5	23

Table II--Chemical analysis of 0.100 inch Ti-6Aℓ-4V and 0.001 inch CP titanium foil used in the study.

MATERIAL (HEAT)	C	Fe	Aℓ	V	N_2	O_2	H_2
Ti-6Aℓ-4V (1)	.023	.09	5.8	4.0	.010	.13	.006
Ti-6Aℓ-4V (2)	.023	.09	5.9	3.9	.010	.11	.004
CP Ti	.023	.12	--	--	.013	.12	.002

Table III--Diffusion bonding parameters of the billets

BILLET No.	INTERLEAF MATERIAL	Time (Hr.)	TEMPERATURE (°F)	PRESSURE (psi)
A	0.0015" Aℓ foil	3	1000	6000
B	0.0010" CP Ti foil	5	1700	2000
1	None (full strength)	5	1700	2000

Table IV--Fracture toughness results from precracked Charpy and
larger three-point bend specimens.

BILLET No.	ORIENTATION	FRACTURE TOUGHNESS	ksi $\sqrt{in.}$
		CHARPY	LARGE THREE-POINT BEND
A	arrester	arrest	--
A	divider	62	74.7
B	arrester	86.2	--
B	divider	80.6	89.6
1	arrester	76.4	--
1	divider	82.5	98

Table V--Fatigue life of precracked large three-point bend specimens

BILLET No.	INTERLEAF MATERIAL	PRECRACK LENGTH (in.)	INITIAL STRESS INTENSITY Ksi $\sqrt{in.}$	CYCLES TO FAILURES $R \simeq 0$ P_{max} = 1400 lbs	SPLITTING
A	0.0015" Al foil	0.063	12.7	77,500	yes
B	0.0010" CP Ti foil	0.085	13.8	97,800	no
1	none (full strength)	0.040	11.5	76,000	no

Table VI--Crack growth rate vs. ΔK for material with the divider orientation.

BILLET NO. 1	
K ksi $\sqrt{\text{in.}}$	da/dn in.
12.8	3.12×10^{-6}
16.2	7.00×10^{-6}
16.8	7.73×10^{-6}
19.9	9.1×10^{-6}
21.8	7.0×10^{-6}

BILLET A	
K ksi $\sqrt{\text{in.}}$	da/dn in.
7.3	7.82×10^{-6}
7.3	2.06×10^{-6}
9.2	1.74×10^{-5}
11.1	1.42×10^{-5}
14.5	1.56×10^{-7}
14.5	6.23×10^{-7}
14.8	5.5×10^{-6}
16.2	6.7×10^{-6}
16.8	2.63×10^{-7}
18.1	8.5×10^{-6}
18.8	5.5×10^{-5}

BILLET B	
K ksi $\sqrt{\text{in.}}$	da/dn in.
12	1.43×10^{-6}
12.1	1.4×10^{-6}
13	3.8×10^{-6}
13	9.5×10^{-7}
13.7	5.4×10^{-7}
13.7	4.38×10^{-6}
13.7	4.45×10^{-6}
13.9	2.82×10^{-6}
14	5.3×10^{-6}
16.7	8×10^{-6}
18	8.7×10^{-6}
19.2	1.14×10^{-5}
20.6	2.4×10^{-5}

APPENDIX II

FIGURES
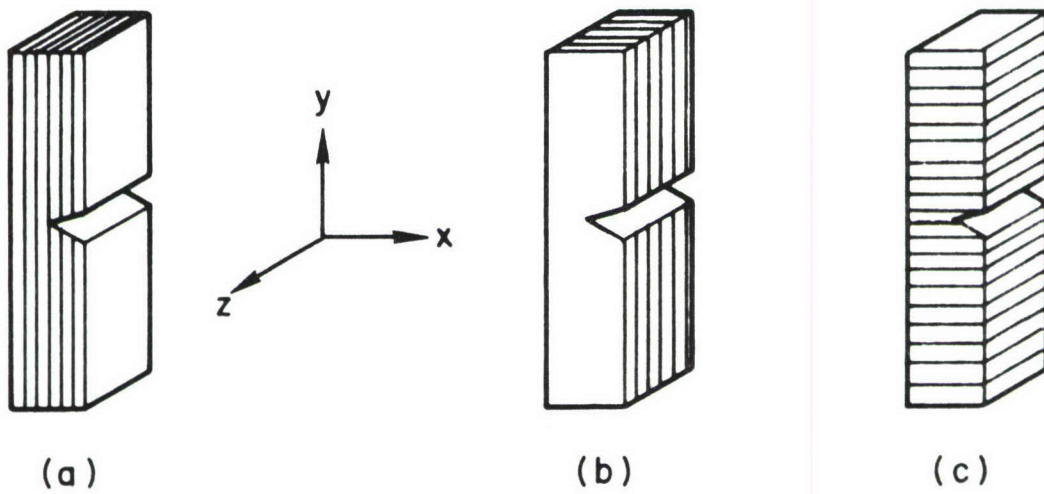
Figure 1. Possible Orientation of the Interface in Relation to the Propagating Crack:
(a) Crack Arrester, (b) Crack Divider, (c) Crack Enhancer
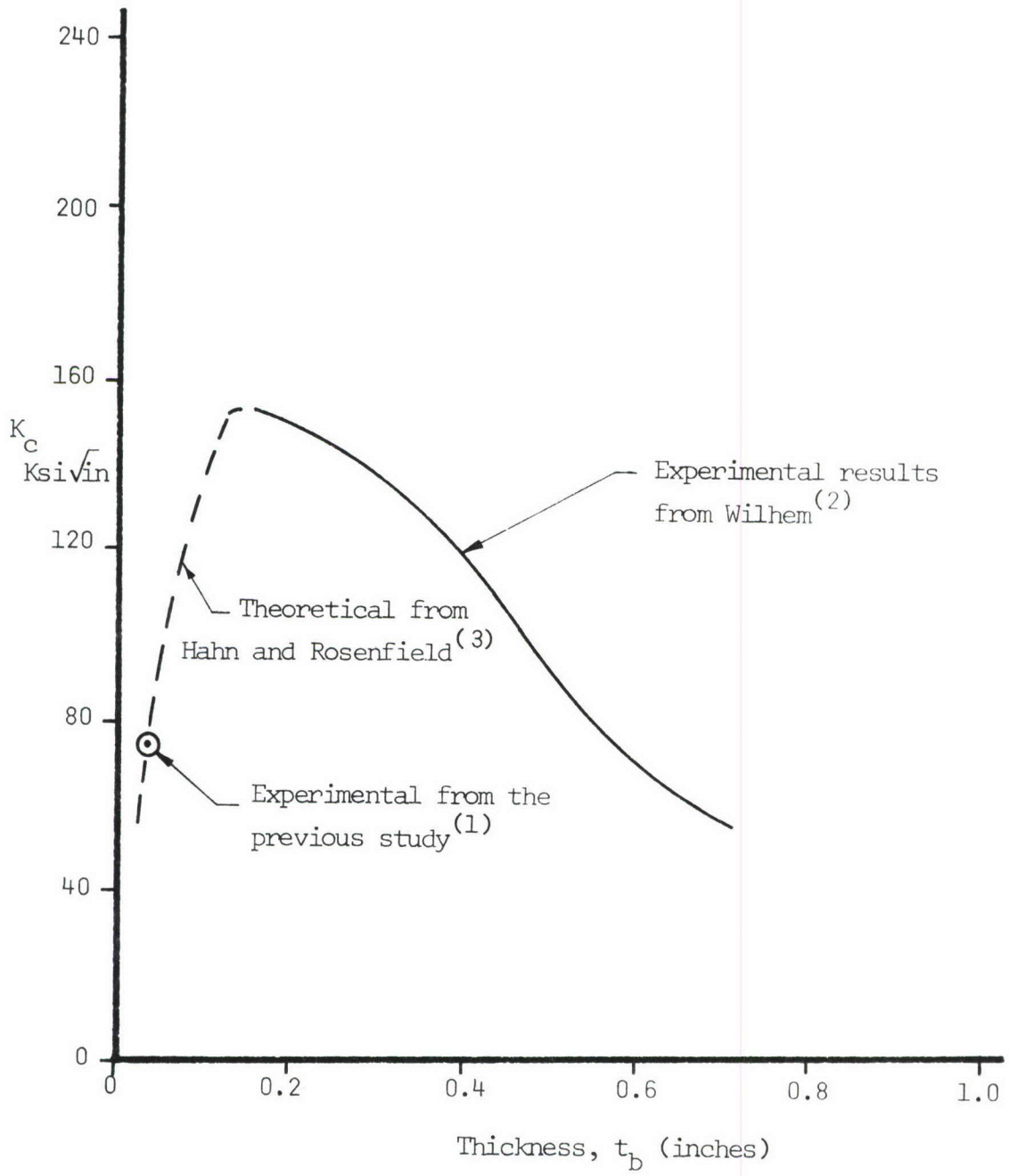
Fig. 2 K_c vs. thickness for 6Aℓ-4V titanium material [see Ref. (1)]
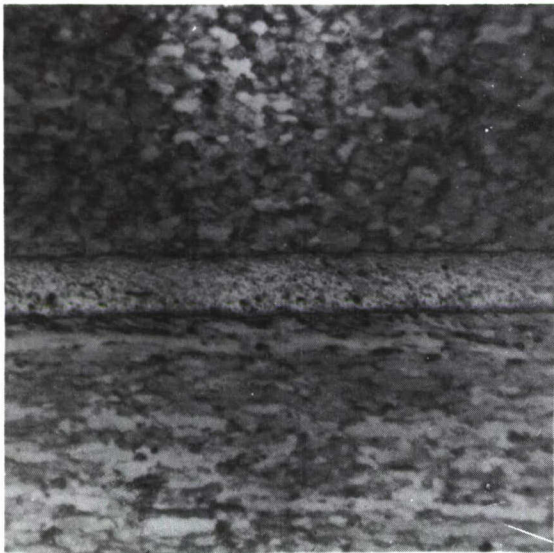
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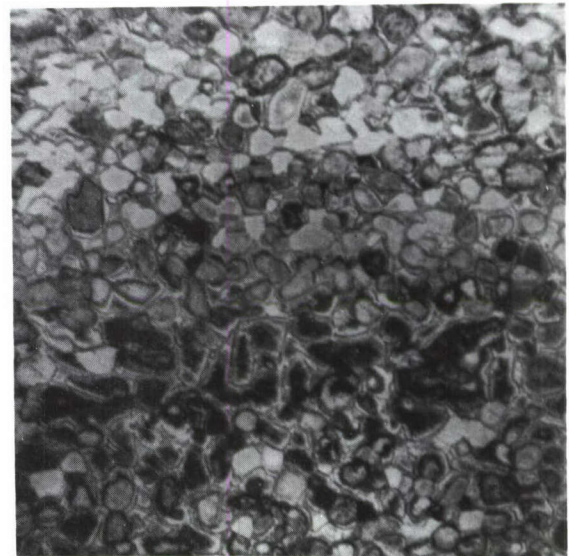
(b)
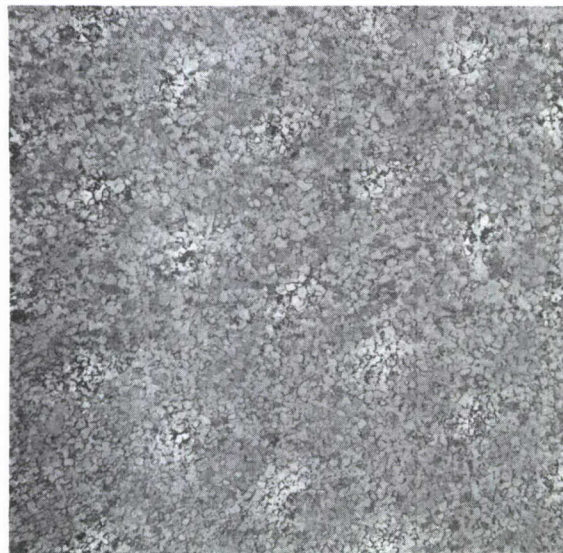
(c)

Fig. 3 Typical microstructure of the billets tested in this work:
(a) Billet A (250X); (b) Billet B (250X); (c) Billet #1
from the previous tudy (100X).[1]
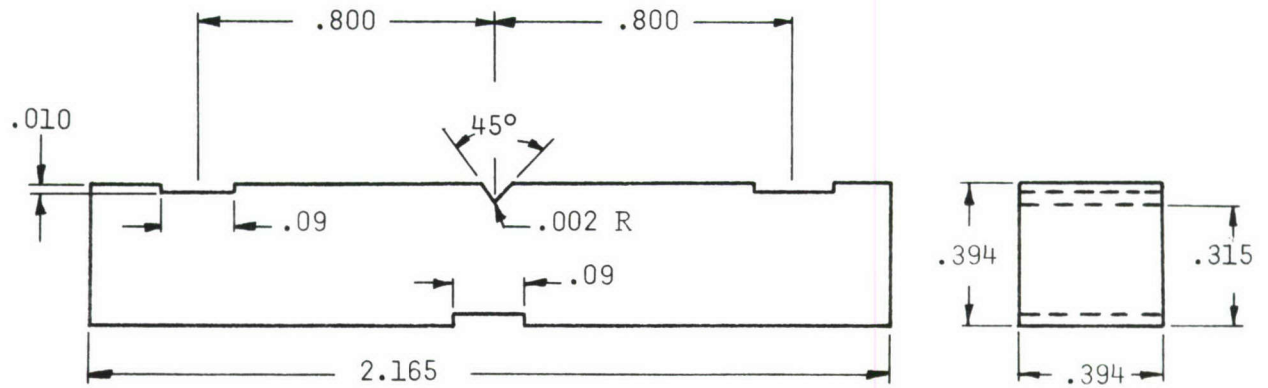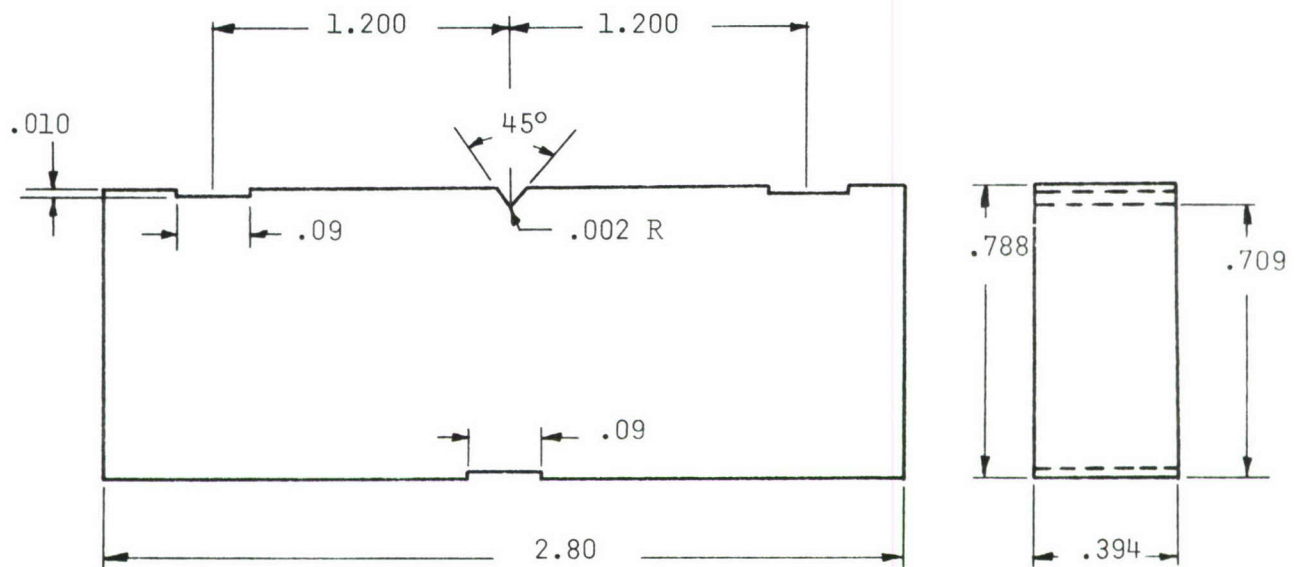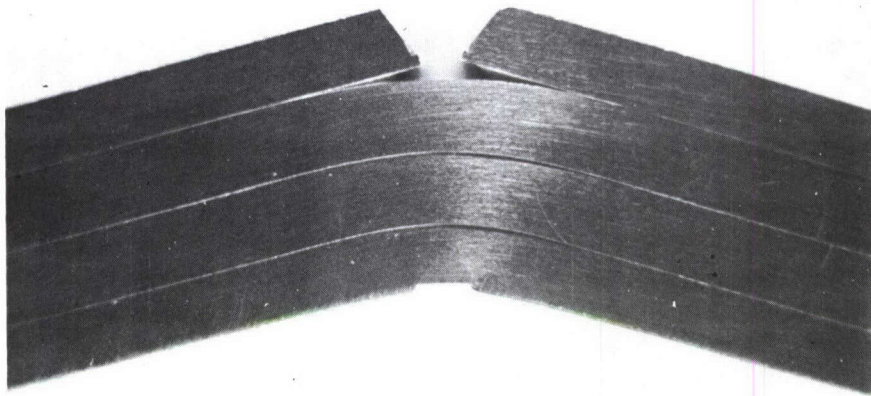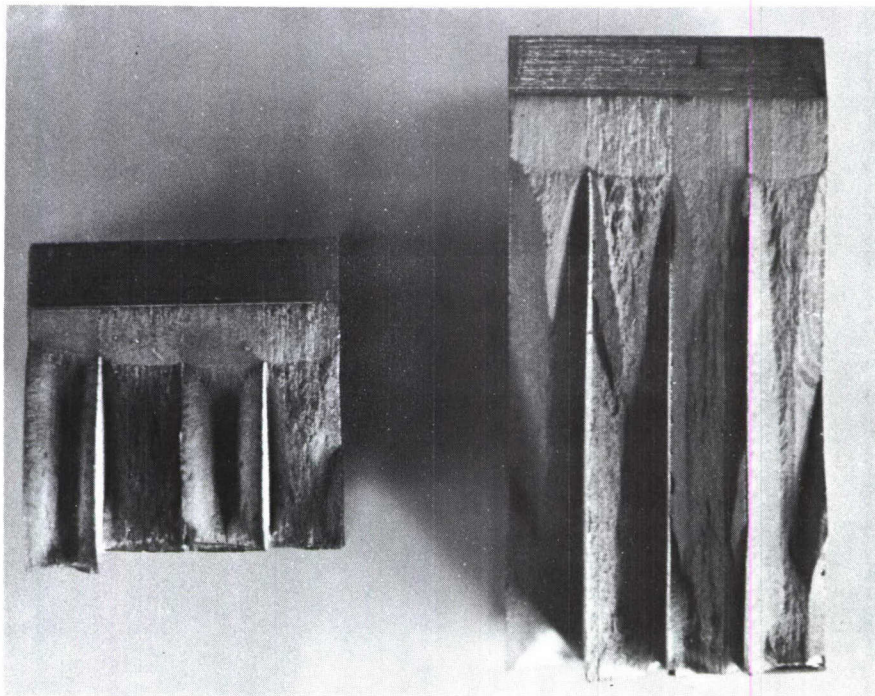
Fig. 4   Charpy specimen used for fracture testing

Fig. 5   Larger three-point bend specimen used
in the fracture studies.

(a)

(b)

Fig. 6 Fracture appearance in arrester orientation (a) and divider
orientation (b) of Billet A.
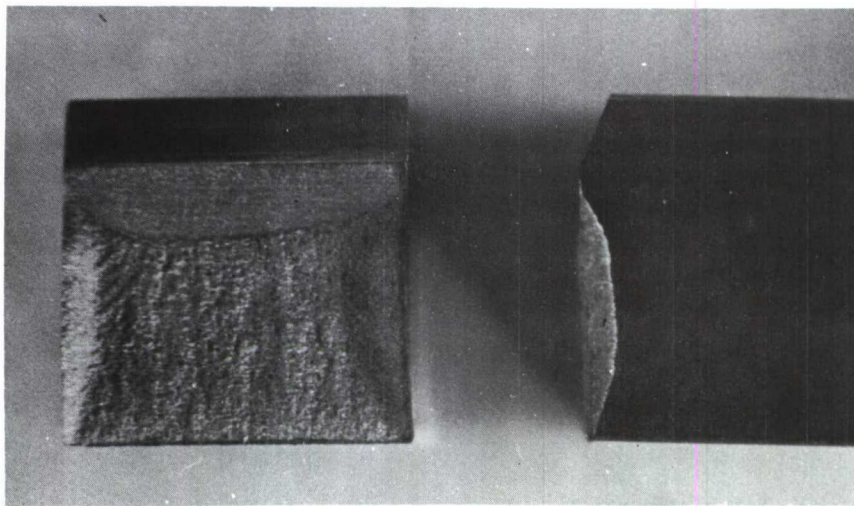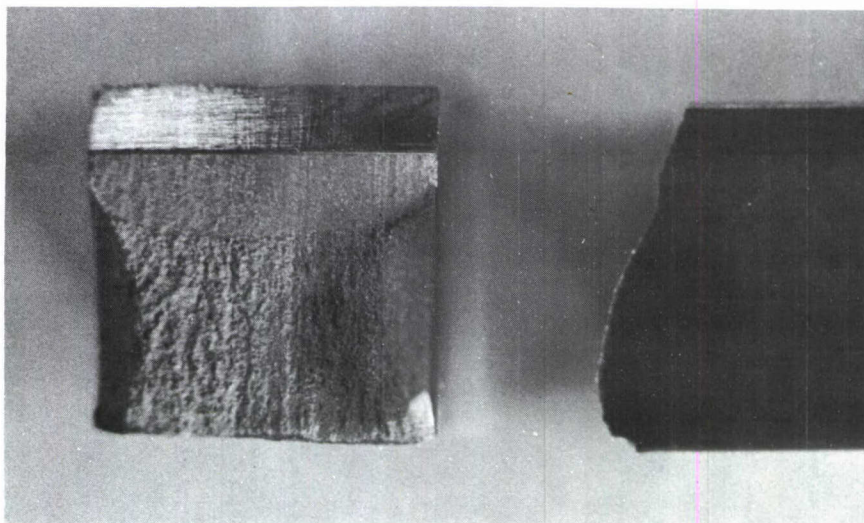
Fig. 7 Fracture appearance in arrester orientation (a)
and divider orientation (b) of Billet B.
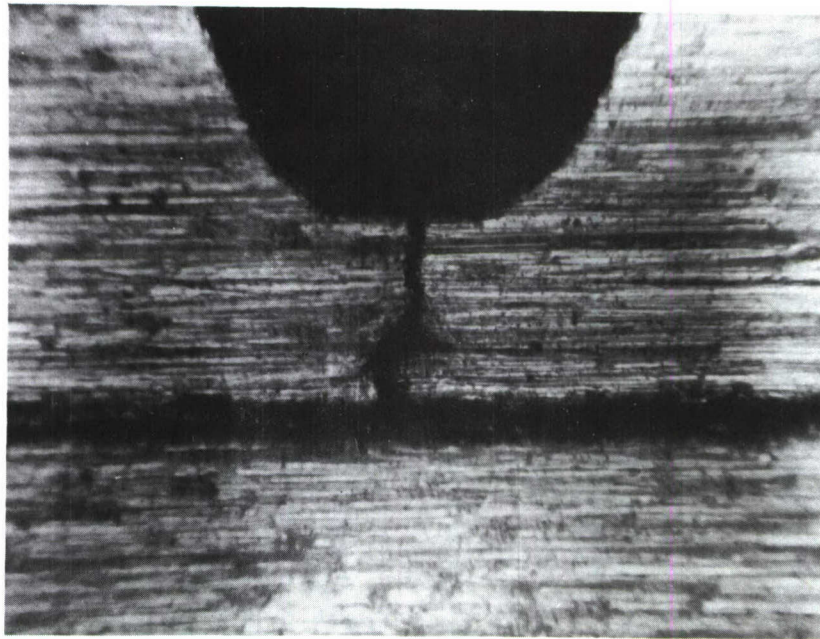
Fig. 8   Crack arrest during fatigue (K_{max} = 11.4 Ksi $\sqrt{in.}$) in
the arrester orientation of Billet A (80X).
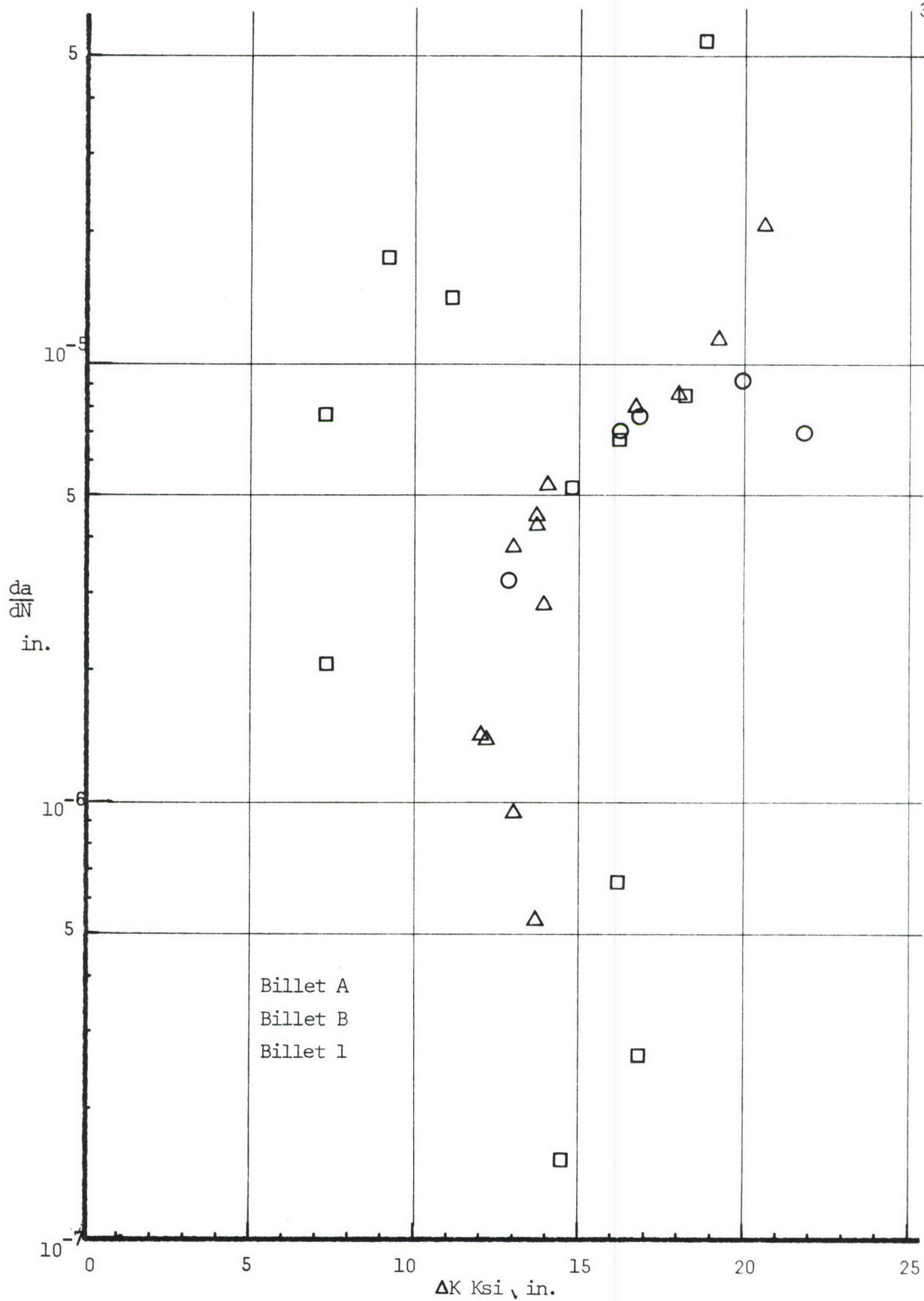
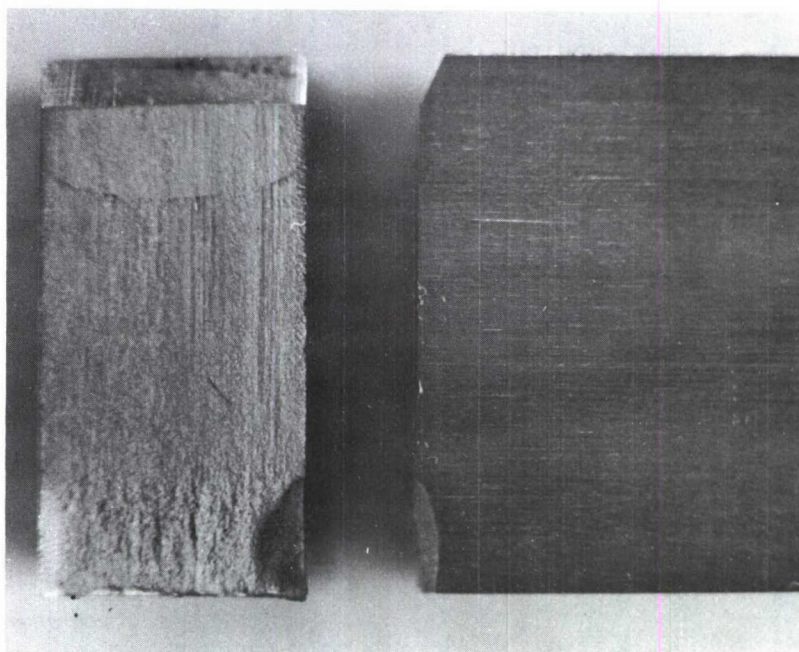Fig. 9 Crack growth rate vs. ΔK for divider orientation of the three billets.
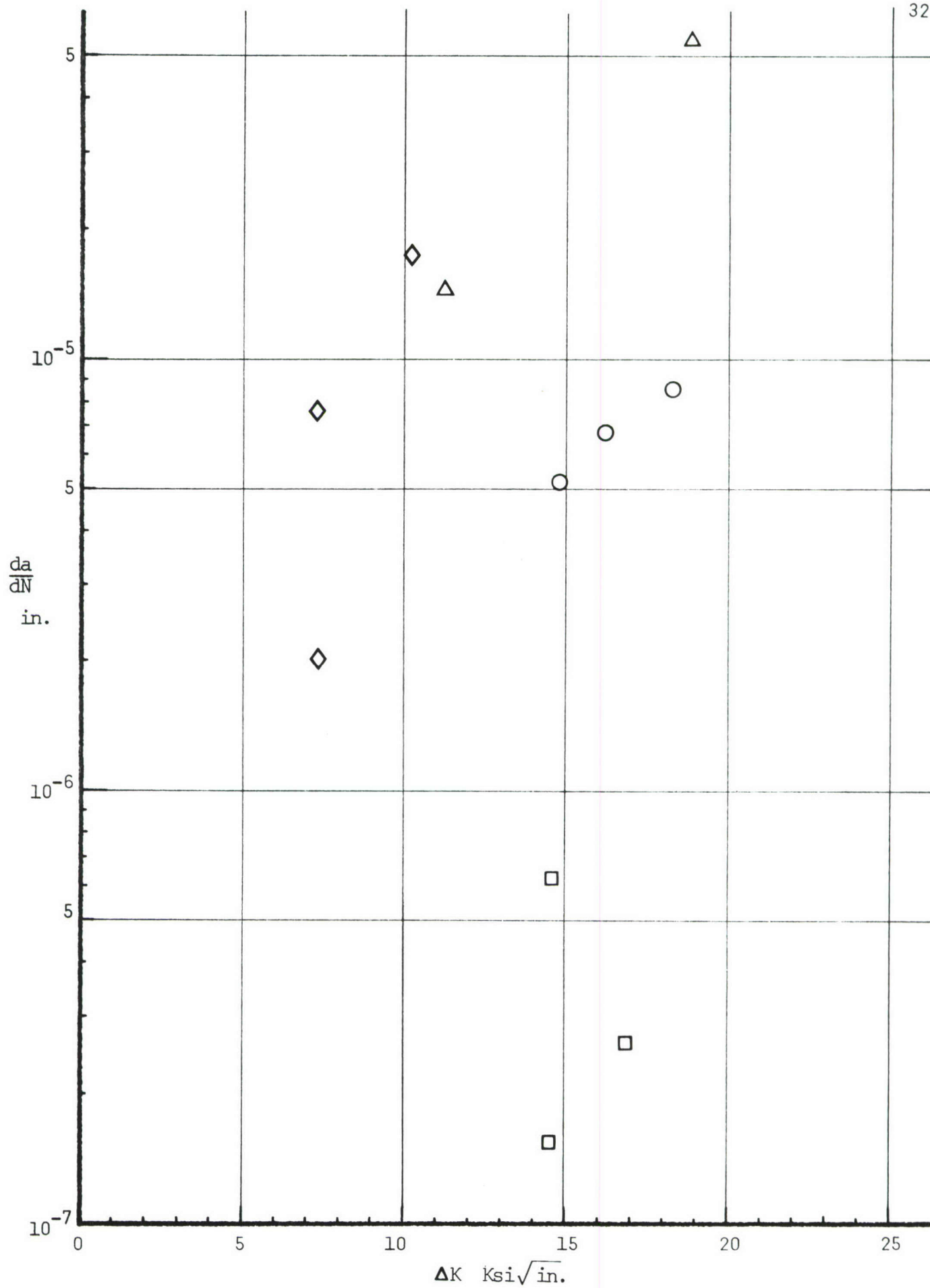
Fig. 10 Crack growth rate vs. ΔK for various specimens of Billet A
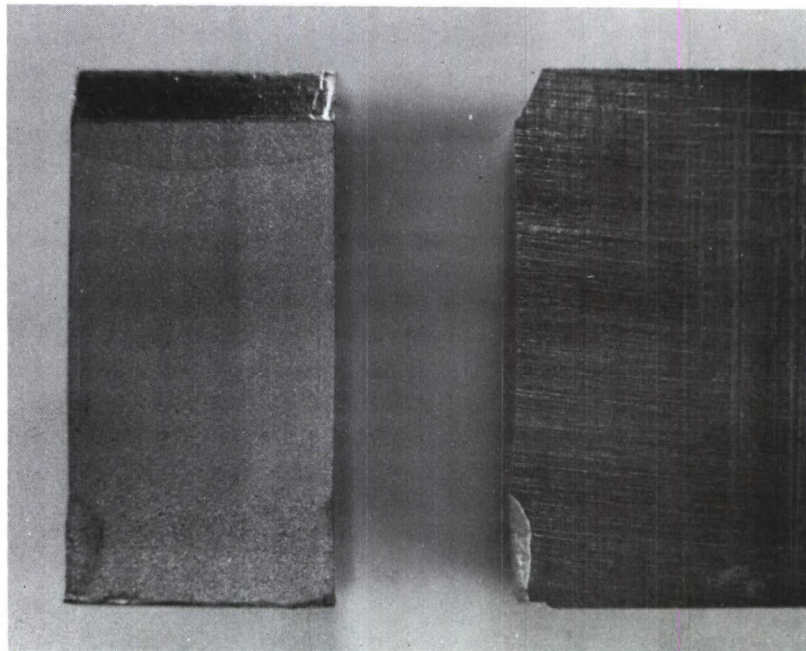(divider orientation).
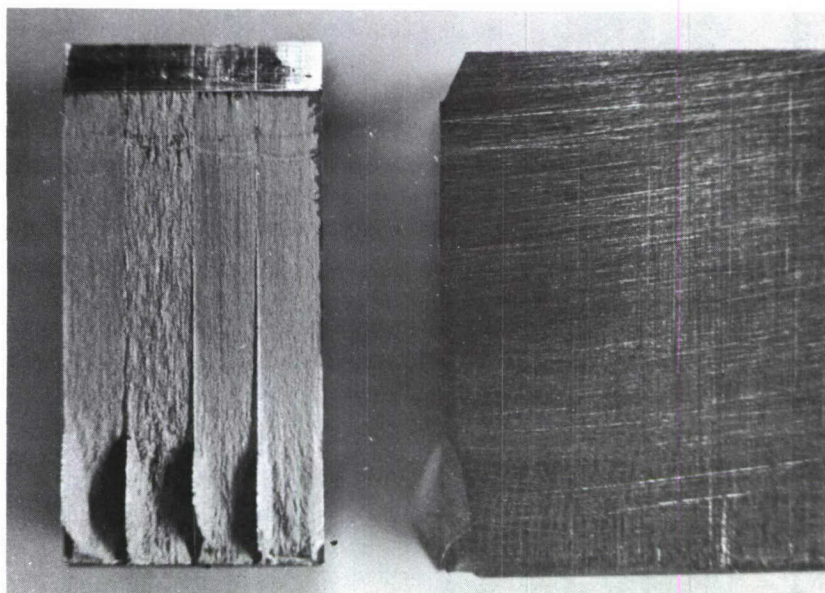
(a)

(b)

Fig. 11 Fatigue in divider orientation of Billet **A** (a),
Billet B (b), Billet #1 (c). The specimens shown
were used for the data of Table VI.
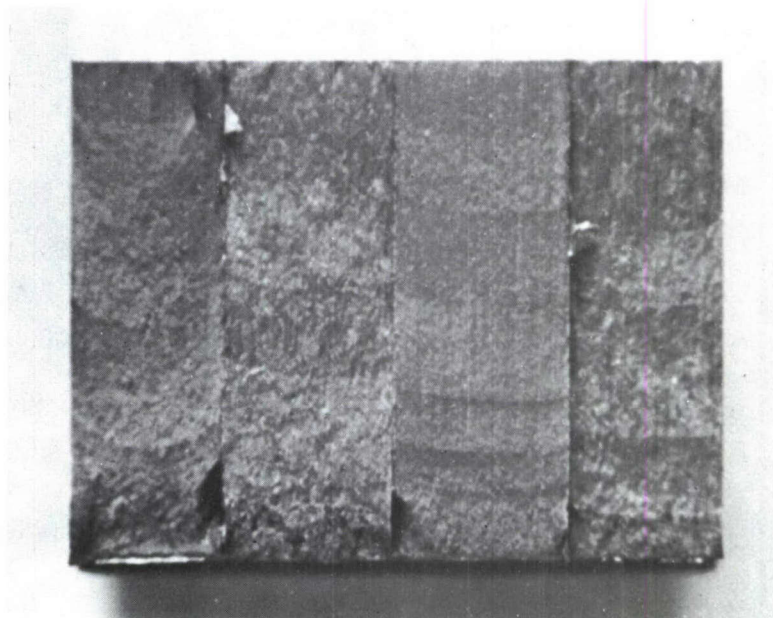
(c)

Fig.11 Continued....

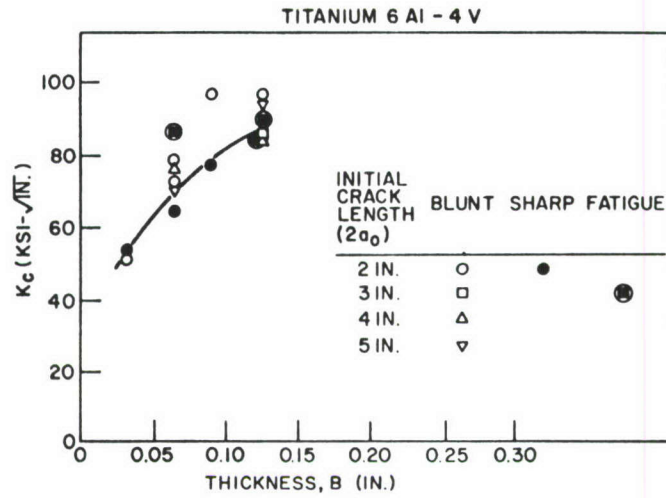Fig. 12 Fatigue specimen from Billet A showing evidence of
crack channeling.

TITANIUM 6 AI - 4 V

Fig. 13 Influence of panel thickness on K_c for Ti-6Aℓ-4V
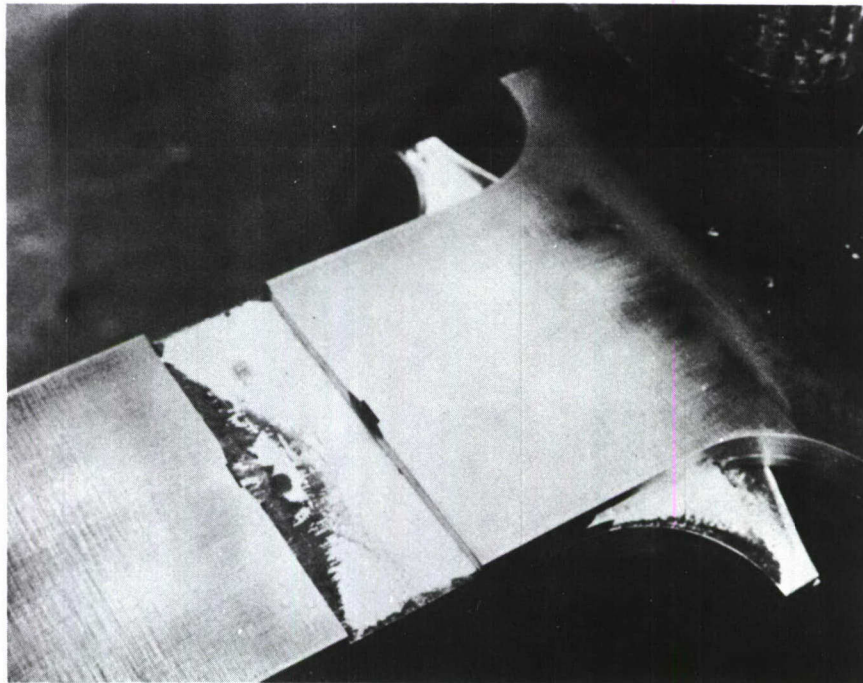specimens. Data from Ref. (5).

Fig. 14 Thumbnail crack specimen tested at AFML showing crack
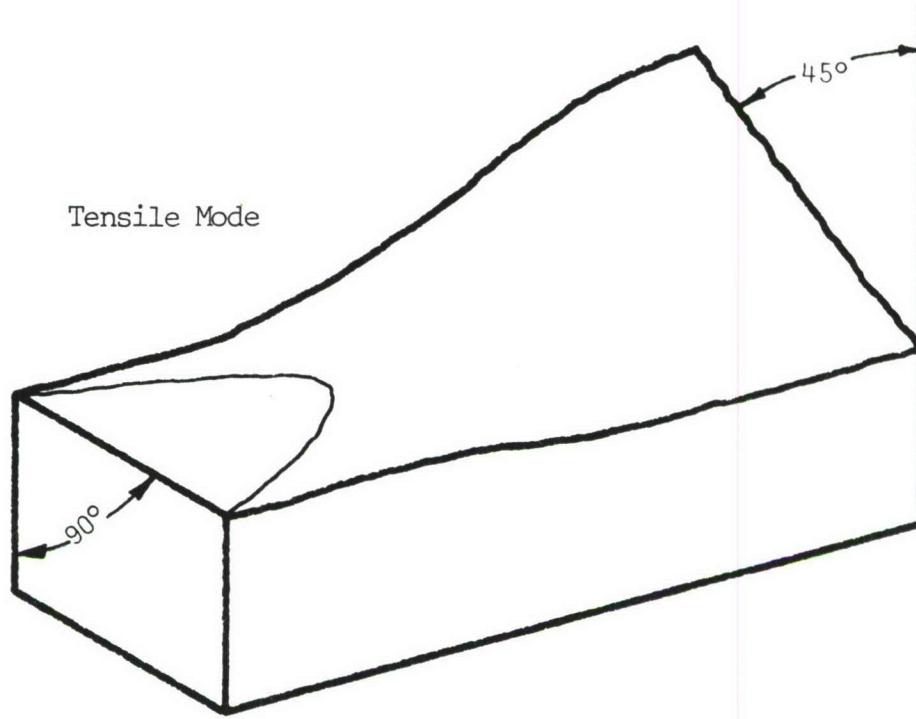arrest and further crack propagation along the inter-
leaf.

Fig. 15 Schematic showing the transition of a fatigue crack
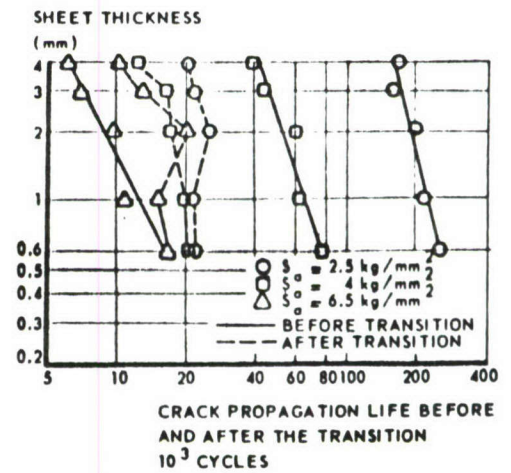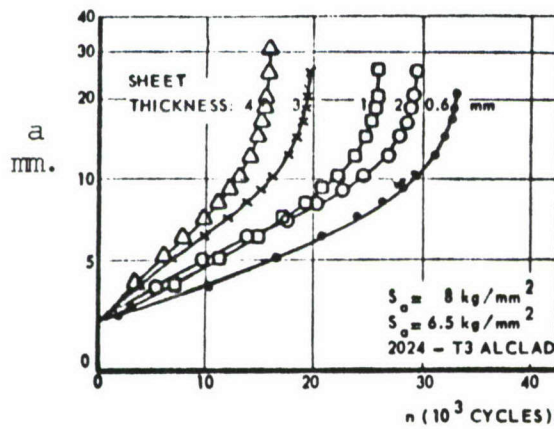in sheet material.

Fig. 16 The influence of sheet thickness on fatigue crack
propagation in 2024-T3 alclad material. Data from Ref. (7).

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13. ABSTRACT

An investigation of the use of laminate composites containing a weak interface to increase the fracture toughness of high strength titanium alloy has been conducted. Two billets were fabricated from 0.010" Ti-6Al-4V material using a diffusion bonding process. Thin metal foils were used as interleaf materials. Results indicate that the use of a 0.0015" Al foil as an interleaf leads to delamination ahead of the crack tip in the arrester orientation, and effectively blunts the crack.

In the divider orientation, splitting of the Al interleaf and plane stress fracture did not lead to the increase in toughness expected over thicker material. However, tests indicate that the base metal used in fabrication has a low K_c value, which may account for this effect.

It was found that a 0.001" commercially pure titanium foil used as an interleaf will not lead to delamination and splitting. Diffusion during the bonding process causes formation of a uniform material with no weak interface. Therefore, no delamination or splitting could occur in the composite material.

It was also found that a propagating fatigue crack can be arrested at the interface in the arrester orientation. It was also determined that the crack growth rates of material which splits in the divider orientation are similar to rates obtained from full strength material.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Titanium Alloy Ti-6Al-4V						
Laminate Composite						
Diffusion Bond						
Fracture Toughness						
Fatigue						